DISCUSSION BEFORE THE RADIO SECTION, 22ND APRIL, 1953

Dr. G. G. Macfarlane: The authors have described the properties of surface waves as if a surface wave can exist as a complete field all by itself, just like an H_{01} mode in a perfectly conducting waveguide. From the behaviour of the surface-wave field at large distances from the surface, it is immediately clear, however, that this cannot be so, and that the surface wave is a pseudo-mode and not a pure one. The surface-wave field is an incoming progressive wave, whereas the field at large distances from the surface must be an outgoing progressive wave. There must therefore always be a radiation field associated with the surface-wave field. The only exception could be if the field were produced by an aperture of infinite extent. The qualitative discussion of Section 9 of the paper by Prof. Barlow and Mr. Karbowiak illustrates this point.

This leads one to consider how the contribution of the surface wave to the total field can be enhanced. This is indeed a big question, on which I hope the authors will have something further to say. There is one facet of it, however, on which I would like to remark. It concerns the ease with which a surface-wave-like field can be launched along a thin resistive wire, but the difficulty in launching it along a planar surface of the same material. The problem is to understand the changes in the field as the radius of the wire is increased indefinitely. In order to find out the answer one can write down the expression for the field due to a ring source of dipoles coaxial with the wire (Fig. A). This can be expressed as an integral with respect to the propagation coefficient along the path of integration shown in Fig. B.

The integrand has a pole at the value of γ for which the

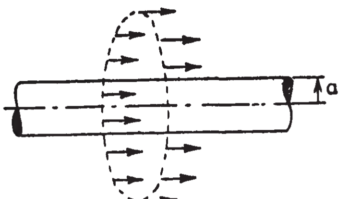

Fig. A.—Ring source of dipoles coaxial with the wire.

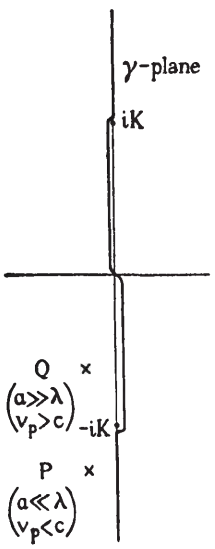

Fig. B.—Path of integration.

reflection coefficient is infinite. This is also the value of γ which gives the Zenneck surface wave. The extent to which the surface wave is excited is the extent to which this pole contributes to the integral. It appears that when the radius of the wire is small the pole is below the branch point $-iK$ at P, and when it is very large the pole is above the branch point at Q. But a pole at Q is separated from the path of integration by the branch cut, which extends from $\gamma = -iK$ to $\gamma = +iK$, and cannot make a large contribution to the integral, whereas a pole at P is adjacent to the path of integration and will contribute appreciably to the integral. From this picture one sees that the surface wave makes a larger contribution to the total field when the wire is very thin than when it is thick. The result can be stated more generally in terms of phase velocity. The phase velocity of the surface wave is greater or less than c according as the pole lies nearer to or farther from the real axis than the branch point $-iK$. Thus for Q, $v_p > c$, and for P, $v_p < c$. The conclusion is therefore that a surface wave can be the major component of the field excited by an aperture of finite width only when the surface reactance is sufficient to make the phase velocity of the Zenneck wave less than c.

In conclusion I would ask the authors whether they have tried loading the surface of a thin wire so much capacitively that $v_p > c$, and if so, whether they succeeded in launching a field having essentially the properties of a surface wave.

Dr. J. A. Saxton: There is now enough practical evidence to show that single wires, at least in straight runs, can be used as efficient waveguides. The authors' work represents a useful extension of the earlier work by Goubau in that it enables one to estimate the performance of single-wire waveguides when the radial decay coefficient is large.

Measurements at 3 000 and 9 000 Mc/s which we have made in the Radio Research Organization of the D.S.I.R. confirm the general validity of the theoretical evaluation of the attenuation to be expected along such waveguides. Calculation shows that at frequencies of the order of 3 000 Mc/s the rate of attenuation along copper rectangular waveguides, of dimensions adequate to sustain only the dominant mode, is of much the same magnitude as that which it is practicable to achieve for the single-wire transmission line. The single wire, however, would appear to have an advantage in relation to permissible mechanical tolerances at frequencies of 10 000 Mc/s and greater, provided the capabilities of the wire are used to the full.

All this is satisfactory for a simple straight wire which requires no supports, but what happens when you want to take the wire round a bend? Our measurements showed that a considerable loss of power occurred at 3 000 Mc/s, of the order of several decibels, when the wire, which was enamelled, was bent into a circular arc of radius 14 metres, giving an angle of about 30° between the axes of the launching and receiving horns. Clearly if this is at all representative it would not be possible to have many bends in a long run of wire, quite apart from troubles due to discontinuities at points of suspension. The introduction of transformers from surface waveguide to coaxial line back to the guide again at all points where a change of direction is required would not be very satisfactory.

Can the authors say from their work whether there is any prospect of reducing the loss at bends owing to the excitation of radiation fields by modifying the dielectric coating of the wire, or by other modification to the surface reactance of the guide?

Turning now to the paper by Prof. Barlow and Dr. Cullen, we have seen that some at least of the theoretical possibilities of the cylindrical surface wave on a wire guide can be realized, but the surface wave over a plain surface seems a much more difficult proposition. The ingenious way in which the various forms of surface wave have been related is much to be admired, but from the point of view of the application of the surface wave over a plane I am still rather in the dark. How does one launch such a wave satisfactorily? This seems to me to be the crux of the whole problem, and I fear the difficulties have been treated all too lightly.

If the Zenneck wave is to get very far along the surface it must be excited by an aperture distribution of great extent in height. Each part of the exciting wavefront as it impinges on the surface at the Brewster angle simply enters the surface, so that the energy needed to maintain the surface wave at the greater distances must come from more remote parts of the exciting wavefront. We have also not been told how the wavefront having the required amplitude and phase distributions is to be provided in the first place. Incidentally, with regard to Fig. 9(*a*) I wonder whether a small error has not crept in. The angle ψ shown is not the angle of incidence but its complement. It is correctly shown in Fig. 5. Should not the distance out to which the Zenneck wave is produced along the surface be $n \tan \psi$, where ψ is the real part of the Brewster angle?

The launching aperture must be large in terms of λ, which obviously rules out anything longer than decimetre or metre waves at most. This means that $\tan \psi$ will not exceed 4 or 5 for propagation over land, and perhaps 30 or so for propagation over sea. It would appear, therefore, that $h \tan \psi$ can hardly be a significant distance for radio transmission in view of the practical limitations imposed upon the height of aperture it is possible to construct.

I therefore cannot really see what would be the point in going to all this trouble to launch the Zenneck wave, especially as the wave is exponentially attenuated—in addition to the $(\text{distance})^{-\frac{1}{2}}$ factor—along the surface, whereas the Sommerfeld surface-wave

component of the total radiation field from an aerial is ultimately attenuated as (distance)$^{-2}$ over a plane earth.

One could possibly envisage the launching at centimetre wavelengths of a fairly pure Zenneck wave over a suitably prepared surface of limited dimensions, but for what purpose? Is it conceivable that one could replace other forms of waveguide by this process? If so, would there be any advantages to be gained?

The surface cannot be of infinite extent. Reflection at the edges, which would upset the required field distribution, could not be tolerated, and therefore the edges would have to be lined with some form of perfect absorber, and on a finite sheet this could clearly lead to loss of energy. Would this possibly not lead to a less efficient transfer of energy than by the more orthodox forms of waveguide?

It is possible that the authors have in mind other applications of the surface wave over a plane interface, and if so it would be interesting to learn what they are.

Dr. R. L. Smith-Rose: Each of the papers contains a reference to a paper by Professor Sommerfeld which was published in 1899, which is an indication that this subject has been of considerable interest over the past half-century or more. While there may be various things that the modern investigator would think not right in Professor Sommerfeld's original work, his conception that waves leaving a radio transmitting station are partly propagated along the surface of the earth and partly radiated into free space still holds.

Some thirty years ago Dr. Barfield and I measured the forward tilt of the electric force in radio waves travelling over the earth's surface. We called it the Zenneck wave, but I wonder now if we were right. We got our ideas from Zenneck's own publications, and we actually measured the extent by which the electric force was found to be tilted forward. Then using Zenneck's work, from those measurements we determined the conductivity of the ground over which the waves were travelling; and by an independent method we took samples of the ground and measured their conductivity and obtained the same answer. So it seems to me that we did confirm the validity of Zenneck's conception of the manner in which radio waves travel along the surface of the ground.

I believe in always trying to understand physically the results of mathematicians, and it has occurred to me, in connection with the paper by Prof. Barlow and Mr. Karbowiak, to raise again the point which I think was raised many years ago by Sir Oliver Lodge. He said that one of the difficulties about wireless transmission is to understand how the lines of force get away from the transmitting aerial; and I should like the authors to clarify Fig. 2, which shows lines of force emerging from the horn, and then the lines corresponding to the waves travelling along the wire. What happens to the lines of force as they approach the end of the horn?

It seems clear that there is by no means unanimous agreement among the workers in this field either on the physical conceptions of the various theoretical aspects of surface-wave phenomena or on their possible applications. I suggest that some considerable clarification might be obtained if the nomenclature of this subject could be rationalized. Workers in the field of wave propagation have always been familiar with induction and radiation fields, and Sommerfeld introduced the terms "surface wave" and "space wave" many years ago. We now have three other classes of wave presented to us, namely Zenneck surface wave, radial cylindrical wave on a flat surface, and Sommerfeld–Goubau or axial cylindrical surface wave. May I appeal, first, for some simplification of all these terms so far as possible; and secondly, for some clear-cut, unambiguous definitions. The practical radio engineer has so far fought shy of the term "surface wave," and he would appear to be justified in doing so until the research workers in this field are agreed on its definition. In B.S. 204: 1943 the term "ground wave" is defined as "a wave which travels virtually along the ground in a manner primarily determined by the electrical constants of the ground." Can a surface wave be defined in the same way with the words "ground" and "surface" interchanged? If not, how is it defined, and what definitions are applicable to the other terms in use?

Mr. G. Millington: In the paper by Prof. Barlow and Dr. Cullen, I prefer to think of the Zenneck wave in terms of an incident wave with complex direction-cosines so chosen that there is no reflected wave. It stresses the fact that exponential attenuation up from the surface must be accompanied by attenuation in the direction of propagation along the surface. I feel that the paper does not emphasize enough the importance of this attenuation in the practical use of the Zenneck wave on high and medium frequencies and in relation to the problem of launching a sufficiently pure surface wave.

The treatment in terms of direction-cosines also shows very simply that, for waves travelling at low angles of elevation, a field near the surface due to a complex system of incident and reflected waves possesses a characteristic tilt that is not peculiar to the Zenneck wave. Thus, answering Dr. Smith-Rose's question, the measurement of the tilt of a ground wave at the surface of the earth, while enabling one to deduce the earth constants, is not sufficient to tell whether the wave is of the Zenneck type.

The radial cylindrical wave and the Goubau surface wave are closely related mathematically, for by comparing the values in eqns. (10) and (12), an essential point is that γ and u_2 change places with respect to the Hankel and the exponential functions. The reason for this would appear from a unified treatment in terms of cylindrical co-ordinates, putting $d/d\phi$ (or $d/d\theta$) $= 0$ and using a separation constant.

The arguments illustrated in Figs. 7B and 8 are illuminating, but I feel that it is somewhat artificial to compare the Zenneck wave with one which by itself does not satisfy the boundary conditions between the plates in Fig 7B; while, however far apart the plates in Fig. 8 may be, the argument holds only if the space between them is symmetrically fed, and cannot strictly be applied to describe the properties of the wave over the surface of one of the plates when the other is removed altogether.

In the mathematical discussion of the curved surface in Fig. 10, the essential eigen-value nature of the analysis should be brought out. It is not really correct to state that the incoming travelling wave can be rejected, except in so far as it is required to supply losses at the surface. At indefinitely large distances there can only be a single outgoing wave, and the existence of an inward travelling wave at the surface required to satisfy the boundary conditions is explained by the Stokes phenomenon that arises in the form of Hankel functions of large and nearly equal order and argument. As far as I can see, the final discussion of the permissible curvature does not depend on the preceding Hankel analysis, as the phase velocity is the flat-earth value due to the loading of the surface, and eqn. (70) is derived from a purely geometrical argument.

Finally how does the behaviour of the model depend on the thickness of the dielectric slab? Mr. Isted and I used a rather similar model to demonstrate our land-sea experiments, in which we adjusted the thickness to give the opposite effect of a weak signal on the surface with a rapid height gain. However, we used a different aerial system that was two or three wavelengths above the surface, whereas the authors are using a slot close to it.

Mr. D. G. Kiely: With regard to the applications of the single-wire transmission line, it has been stated by the authors and by previous speakers that these should be mainly applicable to the centimetric part of the spectrum, but I should like to point out

one aspect which is a rather serious limiting factor when the single-wire system is used in the open air. It is the effect on transmission loss of water on the wire and the formation of films of dirt and carbon. In 1950 we carried out some experiments on this aspect of the problem and found that on a 50-yd length of horizontal single-wire transmission line the attenuation at a wavelength of 3 cm caused by water film and raindrops was of the order of 30 db. Other experimental work has shown that this increase of attenuation due to raindrops is less at longer wavelengths. At a wavelength of 10 cm the effect was measurable on practical aerial feeder lines, and at metre wavelengths the influence of rain was found to be practically negligible.

For these reasons I consider that the main application of non-shielded single-wire line exposed to the open air should be in the metric part of the spectrum, not the centimetric. Further support of this conclusion is obtained by considering the inherent attenuation of other transmission systems at these wavelengths. At metric wavelengths the best cables are much more expensive and some ten times more lossy than a single-wire line, whereas at centimetric wavelengths a well-designed line has the same order of loss as a waveguide, which is admittedly more expensive.

An important point in the paper by Prof. Barlow and Mr. Karbowiak is the correction of Goubau's expressions for field extension as a function of the thickness of the dielectric coating. Goubau's expression led one to believe that the field shrank continuously around the wire as the dielectric thickness was increased, while the authors have shown this to be false and that the field shrinkage is not indefinite and has a limiting value governed by the dielectric constant. This result is important in the design of launching devices for metre wavelengths where the field extension is large and the dimensions of the launching device have to be made as small as possible. It is suggested that the use of a material of high dielectric constant as a matching section at the launching device might be a satisfactory technique to obtain considerable field concentration.

In the original American papers I found rather attractive the method of expression of the field fall-off from the wire in terms of radii within which given percentages of the power flow occurred. It gives a clear physical picture of the geometry of the power flow, and it would add to the present paper if these terms could be incorporated, together with the Hankel-function expression for field decay, which, although describing the field accurately, does not give such a clear physical impression of the transmission system.

Mr. B. I. Stuart: In Fig. 9 of the paper by Prof. Barlow and Mr. Karbowiak, the distribution of the experimental points around the interpolated line seems to follow a sine law. That may be coincidental or it may have some logical explanation. Quite possibly some sort of cylindrical surface wave is launched at the join of the terminating plate and the guide, goes towards the perimeter, gets reflected in a number of Zenneck waves and thus sets this pattern. That may be a measure of the "goodness" of the connection between the waveguide and the terminating plate, and if the standing wave is too "bad" it can introduce serious errors.

I suppose this point could be checked by matching the perimeter by graphite paint and seeing whether we could get rid of standing wave. However, I may have read more into this graph than it was intended to convey.

Mr. L. Lewin: There is one simple demonstration which might have been done. That is to show the effect of moisture on the wire. If a small piece of dry blotting paper is hung over the wire, there is no effect on the received power. However, it is only necessary to damp the paper in order seriously to reduce the propagation past it. I think this supports what Mr. Kiely has said about the effect of weather on the wire, and there is no doubt that at microwave frequencies, at any rate, the wire needs some sort of weather shield. This complicates the use of the wire, the most promising one I have seen to date being a feeder run from the bottom to the top of a microwave tower.

The radial propagation coefficient of the bare wire depends not only on the surface resistance but also on the properties of the air dielectric surrounding it. A change from dry to humid air will affect the spread of the wave and could alter the match at the feeding horns. This would lead to mismatches on a feeder, with consequent distortion when used with a frequency-modulated multi-channel link; and I think this is only one of the reasons against the use of this feeder in what might otherwise appear to be an ideal situation.

With regard to the point raised by Dr. Macfarlane, it might appear at first sight that the power is leaving the line and that the negative phase is simply an example of the recently determined cases in which the phase velocity is in the opposite direction to that of the power flow. However, on closer examination it is seen that the power concerned is really flowing in towards the line, the apparent exponential rise resulting from ignoring the axial component of flow—the total incoming wave is damped. However, the power at the source certainly flows away from the wire towards infinity. A small amount is drawn back to feed the wire, and at a sufficient distance from the source it might appear that there is an incoming wave. Actually, to get a pure surface wave we would need to be at an infinite distance from the source, and with a finite power and a non-zero attenuation there would be effectively no wave. Hence a pure surface wave is an abstraction; no difficulties arise when a very slightly impure wave fed by a source is considered. Such a case is treated in the M.I.T. Waveguide Handbook*—a coaxial line with infinite centre conductor. An approximate representation of the lines of power flow is shown in the upper part of Fig. C.

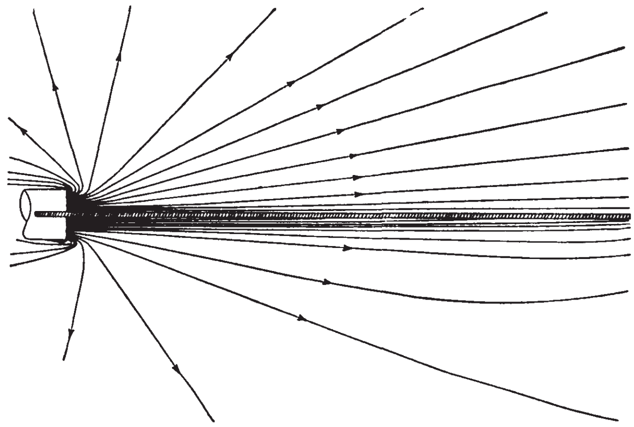

Fig. C.—Power flow from source to guide line. Upper part of Figure refers to an unattended wave; lower part shows the effect of surface resistance.

The lower half shows the bending in of the power flow when the resistivity of the wire is taken into account. The "fictitious waves from infinity" are seen to be provided the whole time by the source. These remarks should also be pertinent to the size of aperture needed to feed a Zenneck surface wave.

Mr. J. G. Linhart: About a year ago I investigated theoretically the radiation from electrons propagating parallel to a dielectric surface, by means of the eigen-function expansion.† During this treatment I used the eigen-functions of the available space, and I have found that the effect was equivalent to the excitation of the surface waves.

* Marcuvitz, N. (Editor): "Waveguide Handbook" (McGraw-Hill, 1951), p. 208.
† Heitler, W.: "The Quantum Theory of Radiation" (Oxford University Press, 1944), p. 40.

The surface wave of a dielectric semi-space with a vacuum above it does not require any component wave coming from infinity towards the dielectric interface. It may be derived from a phenomenon of total reflection. Therefore, in the treatment of excitation or absorption of these waves, which are really formed by plane waves propagated towards the dielectric interface at an angle smaller than the Brewster angle, the wave coming from infinity towards the dielectric does not come into the picture at all.

In this connection I have also studied the prevention of radiation from a bend, and it seems fairly straightforward that it can be minimized provided one uses a material with a continually varying dielectric constant in the radial direction.

Mr. R. B. Dyott (*communicated*): It has been suggested that the loss associated with the launching of a surface wave on to a wire from a conical horn is due to radiation of the unwanted component of energy.

I should like to draw attention to a possible alternative theory which I put forward in a paper on the subject last year.* The theory is based on the fact that any complementary waves, i.e. waves other than the principal surface wave, which are generated by the horn boundary lose their energy as heat generated in the conductor almost as soon as they are launched. A complete analysis of the behaviour of the principal and complementary waves is given by Stratton,* but briefly the essential difference between them can be appreciated by considering the field distribution in each case. The field of the principal wave is concentrated in a very thin layer near the conductor surface; consequently there is relatively little loss of energy. The complementary waves, however, have a field distribution which is nearly uniform across the conductor, so that a large amount of their energy is absorbed as heat, and they are damped out very quickly.

I have attempted to show by analysis that the launching horn does generate complementary waves, and it is interesting to know that the authors have confirmed that the wave near the horn mouth is impure. The fact that at a greater distance from the horn only the principal wave exists seems to bear out the theory that the complementary waves present on the conductor near the horn are damped out soon after being launched.